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A MAGNETIC TRAP WITH A STRONG MAGNETIC FIELD

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Description of a method of injecting intense beams of fast neutral hydrogen atoms into a magnetic trap by ionizing a portion of the atoms with the aid of a strong magnetic field. It is shown that the problem of achieving and maintaining a superhigh vacuum and of creating an injector of fast neutral hydrogen atoms can be solved by using low-temperature techniques. A description is given of the magnetic system and parameters of a new magnetic trap, the vacuum chamber of the trap, and of various components of the hydrogen-atom injector.

One of the possible methods of creating a hot plasma in magnetic traps /421* is that of injecting intense beams of fast neutral hydrogen or deuterium atoms, some of which may be captured in the working volume of the trap because of ionization. Interest in this injection method arose especially after Riviere /422 and Sweetman (Ref. 1, 2) experimentally demonstrated the feasibility of ionizing excited hydrogen atoms by powerful electric or magnetic fields. From measurements of the fraction of ionized atoms, it followed that efficiency of fast ion capture in the trap by this process may be several orders higher than capture efficiency by ionization in residual gas at pressures of the order of 10^{-7} N/m^2.

In conformity with these new data, we decided in the middle of 1962 not to finish assembling the GVL-1 magnetic trap schematically described in (Ref. 3), designed to operate at magnetic field values of B_0 = 2 ml** in the center, but to produce a new trap, the GVL-2, differing from the GVL-1 chiefly in the intensity of the magnetic field.

From published works on the ionization of excited hydrogen atoms by electrical and magnetic fields, it is known that the portion of ionized atoms increases as the field grows larger, and does so especially rapidly, as follows from the findings of Kaplan et al. (Ref. 4) in the region of (1 - 2.5) x 10^4 kV/m. It would, therefore, be delusory to build a trap in whose center the magnetic field exceeded 10 ml during an adequate period of time.

The experience amassed in our laboratory in producing powerful magnetic fields in coils refrigerated to low temperatures (Ref. 5 - 8) indicates that this problem is quite soluble for any reasonable trap volume, when the proper power sources are present. Having at our disposal, however, only comparatively small power sources (capacitor battery of capacitance C = $1.75 \cdot 10^{-2}$ f and

* Numbers in the margin indicate pagination in the original foreign text.
** Note: ml designates Maxwell.

voltage U = 5 kV, and a battery of 100 automobile storage batteries with a total emf of 1200 V) and having selected an internal trap diameter of the order of 5 cm and a pulse length of the order 1 sec, we thus predetermined a maximum attainable field in the center of a single coil of about 10 ml. Without dwelling on this in greater detail, since these questions are clarified in a separate article (Ref. 9), we would like to note merely that the respective field and time values may be derived only because the coils are refrigerated to a low temperature. The use of low-temperature technology, as we will see below, also permits successful solution of the problems of achieving and maintaining a superhigh vacuum and of creating a fast neutral hydrogen atom injector. In proceeding to describe the design and basic units of the GVL-2 trap, let us remark that the vacuum system and injector of the GVL-1 trap lie at the basis of the GVL-2. If necessary, the GVL-2 could be converted into the GVL-1, or into a trap with other parameters simply by replacing the magnetic field coils. We would like to add that even now, despite the small diameter of the trap, in intensity of the magnetic field produced, for its radius it is only slightly inferior to the "Ogra"* (Ref. 10).

<u>Description of Apparatus</u> /423

Figure 1 gives a diagram of the first version of the GVL-2 trap which is presently in operation. The basic units of the trap are the magnetic system or trap proper 1, vacuum jacket 2 with evacuation equipment and injector of fast neutral hydrogen atoms consisting of source 3, recharge chamber 4, and chamber 5 for receiving the beam of neutral particles which have passed through the whole system without ionization. The diagram of our device does not, in principle, differ from those of similar devices already described in the literature (Ref. 1, 2), in which the hot plasma is also created by injecting fast neutral hydrogen atoms into the trap. However, the approach to solving the basic engineering problems in our case and in the mentioned papers is essentially different. Therefore, when describing the units in the GVL-2 trap we will dwell principally on the features of new engineering solutions.

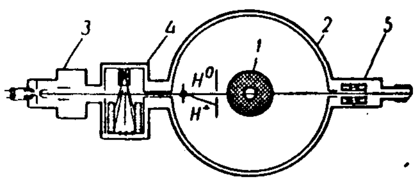

Figure 1

Diagram of the Device -- Cross Section Along the Axis of the Injected Particle Beam.

Magnetic System and Trap Parameters. The magnetic system of trap GVL-2 consists of two series-connected coils made of ordinary copper wire of PBD grade 1.81 mm in diameter, with the winding parameters

$$a_1 = 2{,}5\ \text{см};\ \alpha = 4{,}3;\ \beta = 4{,}4;\ B = 2{,}1 \cdot 10^{-2} l.$$

* Translator's Note: Soviet thermonuclear mirror machine.

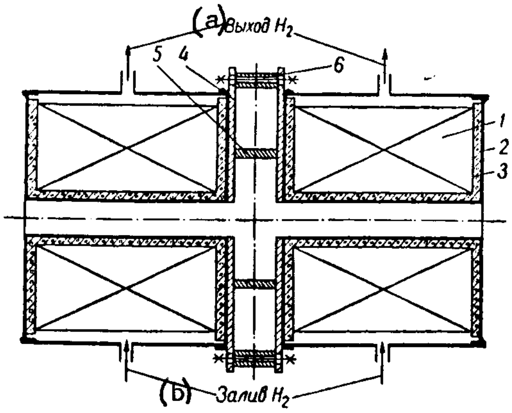

Figure 2

Schematic Layout of Trap Magnetic System.

(a) - Exit H_2; (b) - Inlet H_2

Here a_1 is the inside radius of the winding; α and β are the conventional designations for the ratios $\frac{a_2}{a_1}$ and $\frac{b}{a_1}$ (a_2 and b are inside radius and half of winding length, respectively); and B (in ml) is the field in the center of a single coil at current I in amperes.

Figure 2 schematically shows the coil design and mutual coil arrangement. /424
The windings of coils 1 are continuous and solid with a space factor of $\lambda = 0.6$ and number of turns N in each coil of 4280. The rated inductance of these coils is L = 0.8 henry; ohmic resistance at room temperature is $R^{300} = 11$ ohm. They are located in hermetically sealed housings 2 of stainless steel with wall thickness of 2 mm. Between the windings and housing walls there is an insulating layer 3 designed to operate at a voltage up to 5 kV, and tested at 10 kV. Since, when the magnetic field is switched on, substantial forces of attraction are generated (as was demonstrated by computations and special experiments on models, these forces may be hundreds of kilonewtons in the case of maximum attainable fields and small intercoil distances), support collars 4 made of stainless steel with 8-mm wall-thickness are fastened to the internal faces of the coil housings. Between the collars, at a diameter equal to average winding diameter, there are four pegs 5 15 mm in diameter. Part of the load, moreover, rests on cylindrical sleeves 6 put on over tie bolts. By changing the length of pegs 5 and sleeve 6, we may vary the distance between coils -- i.e., trap length and mirror relationship. At present, the spacing between support collars is 5 cm, between winding ends -- 7.5 cm, and between coil centers -- 29 cm. Inasmuch as the inside diameter of the tube on which the coils are wound is 4.5 cm, and distance L_0 between trap mirrors is somewhat less than the spacing between coil centers and is about 27 cm, we derive the value

$$V = 3{,}35 \cdot 10^{-4}\ \text{м}^3.$$

for the plasma volume in the trap.

Coil arrangement inside the trap vacuum jacket, whose design will be briefly described below, is clearly seen in Figure 3. Coaxially fastened together with tie bolts, they are located on a stand of stainless steel rigidly connected to the jacket wall. Stand height may be regulated within several /425
centimeters, thus permitting the trap axis to be shifted within the necessary limits with respect to the axis of the injected particles.

The coils, which, as mentioned above, are series-connected, are powered through carefully insulated lead-in wires, laid in long German silver tubes 16 mm in diameter carried to the outside of the trap vacuum jacket. The cross section of the copper lead-in wires is several times greater than that of the winding wire. A very insignificant amount of heat is delivered along it to the coils, and corresponds to evaporation of approximately $4 \cdot 10^{-6}$ kg of liquid hydrogen per second. In Figure 3, the tubes in which the lead-in and connecting wires are laid are easily distinguishable, because they are led out onto the faces of the coil housings.

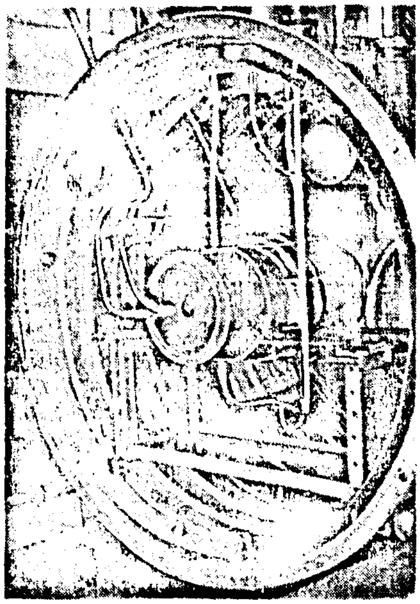

Figure 3

General View of Vacuum Chamber and Coil Arrangement.

The coils were refrigerated in two stages: first to 78°K by liquid nitrogen, and then to 20.4°K by liquid hydrogen. The liquid refrigerants enter the coil housings from below through a German silver pipe which branches on the bottom, pass -- while vaporizing -- through an annular channel between coil winding and housing shell, and their vapors (N_2) are vented to the outside through a buffer volume or (H_2) are led out to a gas tank. When the coils are completely refrigerated to the corresponding temperature, liquid N_2 or H_2 fills both the free volume of the coils and the buffer volume. If necessary, they may be completely evacuated through the same tube used for the inlet. The amount of liquid nitrogen and hydrogen needed to refrigerate the coils and their casings is 0.075 and 0.035 cubic meter, respectively. Coil refrigerating rate was determined from the change in coil ohmic resistance during continuous delivery, first of liquid nitrogen, and then of liquid hydrogen. Because of the great thickness of the coils and the lack of channels for the refrigerant liquids, this rate is low and averages about 30 deg/hr. It is gratifying that in the working temperature range from 50 to 20°K (Ref. 9), coil refrigeration takes place approximately two times faster. This means that under our conditions the repetition frequency of the working current pulses can be no less than two per hour when the maximum field has been reached.

The ohmic resistance of a pair of coils when they are completely refrigerated to hydrogen temperature is 0.21 ohm, i.e., 105 times less than at room temperature. Therefore, the initial power required to produce a field of the order of 10 ml in the trap mirrors is only 50 kw. Busol et al. (Ref. 9) discuss these matters in greater detail.

If the field in the center of one coil is given, then the field in the center of the trap and, consequently, the mirror relationship is determined by inter-coil distance h. Field distribution along the system axis was computed from familiar formulas and is shown graphically in Figure 4 for the two /426 cases of h = 5 cm and h = 7.5 cm. Distance from trap center to external edge of the coils is laid off on the x-axis; on the y-axis -- the total field B from the two coils under the condition that the field at the center of one coil is exactly 10 ml. From the figure it is clear that in both cases the fields in the mirrors differ only insignificantly from each other and exceed the field at the center of one coil by only a few percent. The difference in values of the magnetic field in the system center for the indicated values of h is, however, more substantial. The numerical values of the field at trap center and of the mirror relationship for both values of h given in the figure indicate that a mirror field of B_m = 10.5 ml must be produced to achieve the B_0 = 7 ml which is the basis of the calculations (Ref. 12) on plasma accumulation in our trap, when h = 5 cm.

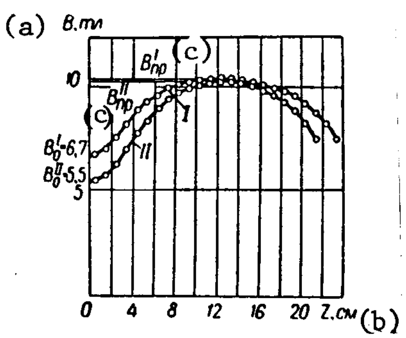

Figure 4

Field Distribution Along Trap Axis:

I -- h = 5 cm, II -- h = = 7.5 cm.

(a) - B, ml; (b) - Z, cm; (c) - B_m.

Radial distribution of the field in the trap median plane was experimentally found and is given in Figure 5 for h = 7.5 cm. The values plotted on the y-axis in this figure were obtained in experiments with unrefrigerated coils at a current of I = 4.5 amp. Here, it was important for us to know principally the value of ΔB by which the field grows when radius is reduced from 2.5 cm to zero, since it is precisely this value which determines the fraction of particles which may be ionized directly in the trap volume. The graph shows that in the given case

$$\frac{\Delta B}{B_0} \cong 7\%.$$

Trap Vacuum Jacket and Evacuation Equipment. Magnetic system 1 of the GVL-2 trap is located within a large vacuum chamber 2, the design of which is apparent from the diagram in Figure 6 and the photograph in Figure 3. It is made of ordinary soft steel and is 1.8 m long with a diameter of 1.2 m. A second feature, both of the vacuum chamber itself and of the entire apparatus, is that ordinary vacuum rubber is used to vacuum-seal all separable joints. In contrast to most modern in- /427 stallations designed to produce a super-high vacuum, our device cannot be heated to the high temperatures (400 - 450°C) which are recommended in super-high-vacuum engineering. We plan, however, to work in a pressure region of the order of 10^{-7} N/m^2. We do this, first, by almost complete screening of the vacuum chamber walls by copper screen 5 refrigerated to nitrogen temperature, and, secondly, by the very high evacuation rates which are easily attainable with hydrogen 4 and helium 3 condensation pumps. The essential feasibility of

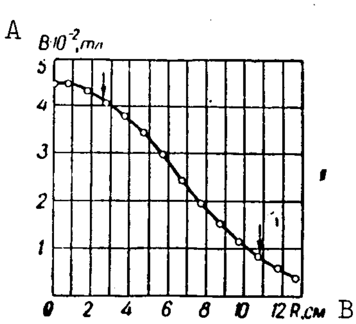

Figure 5

Radial Distribution of Field in Median Plane of Trap When h = 7.5 cm.

(a) - $B{\cdot}10^{-2}$, ml; (b) - R, cm.

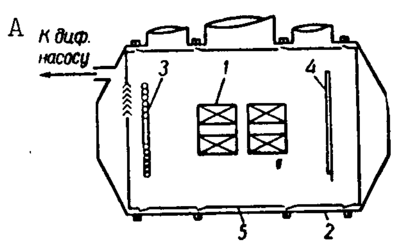

Figure 6

Diagram of Apparatus -- Cross Section Along Vacuum Chamber Axis.

(a) - To diff. pump

producing a vacuum of order 10^{-8}-10^{-9} N/m^2 in a device with rubber seals is demonstrated in (Ref. 13).

For purposes of convenience in installation and mounting of coils, the vacuum chamber, as shown in Figure 6, is made in three separate sections. The length of the center section, in which the coils creating the magnetic field are located, is 0.5 m; the length of the side sections in which the hydrogen and helium condensation pumps are situated is 0.4 m. Each section and the covers have copper screens independently refrigerated by liquid nitrogen. They are made so that, when the chamber is assembled, these screens partially overlap each other to prevent vapor of oil, rubber, etc. from getting into the interior cavity.

The hydrogen condensation pump, whose purpose is principally to pump out all gases not condensing at 78°K before hydrogen is let into the coils, is made in the shape of a copper plate to which a copper tube 30 mm in diameter is welded for thermal contact. It is affixed to the liquid hydrogen tank having a capacity of 0.025 cubic meter, which is mounted in a special fitting in the top part of the section. The theoretical rate of gaseous nitrogen evacuation by this pump is approximately 70 m^3/sec. The need for such a high evacuation rate is obvious, since in unheated installations -- even when there are no leaks at all from without -- there is always a residual gas inleakage because of molecule desorption from the walls. In our case, when the screen was refrigerated to 78°K total inleakage was appreciable -- about $2.5{\cdot}10^{15}$ molecule/sec. Simple calculations show that even under these conditions equilibrium pressure in the chamber will be about $1{\cdot}10^{-7}$ N/m^2 (disregarding evacuation surfaces).

The helium condensation pump is made in the form of a flat, tightly-wound spiral of copper tubing with an inside diameter of 10 mm through which /428
liquid helium is continuously pumped at reduced pressure. The purpose of this pump is to evacuate the hydrogen entering the chamber during operation of the ion source and injection of the beam of neutral particles into the trap.

The outside diameter of the spiral is 62 cm; the inside diameter is about 10 cm. The entire surface of the helium pump is thus approximately 0.6 m^2, i.e., hydrogen evacuation rate is about 260 m^3/sec. If it is assumed, however, that every H_2 molecule before condensation collides at least once with the nitrogen screen, the evacuation rate will be approximately two times less and will be about 130 m^3/sec.

The great volume of the trap vacuum jacket and the immense hydrogen evacuation rate (which may easily be increased by several factors) enable us to deflect the unrecharged component of the ion beam directly in the device, as is schematically shown in Figure 1, by somewhat shortening the distance from ion source to the trap. Since the population of the excited levels of the hydrogen atom rapidly decreases with increased distance from the source (Ref. 14), this fact may be essential in increasing the portion of neutral particles undergoing ionization in the working volume of the trap.

By the use of new data (Ref. 15) on the injection coefficient of hydrogen ions into a heated stainless steel target, we may easily demonstrate the fact that -- even with the given arrangement of the target and helium pump -- an equilibrium pressure on the order of 10^{-7} N/m^2 with an unrecharged ion beam current of up to 10 ma may be maintained in the chamber.

Injector of Fast Neutral Hydrogen Atoms. The Ion Source. To produce hydrogen ion beams, we use a source of the Ardennes type directly attached to the recharging chamber. This means that a mixed beam of hydrogen ions, containing H_2^+ and H_3^+ ions in addition to protons, will proceed to the recharging target. Therefore, the beams of neutral particles forming after ion overcharge will also consist of particles of a different type. Basically, as follows from (Ref. 16), these particles will be hydrogen atoms, but of differing energies -- E, $\frac{1}{2}$E, and $\frac{1}{3}$E, where E is accelerated ion energy. In our experiments, it is 30 keV. It is known from the literature (Ref. 17) that the mass composition of the ion beam depends on the operating conditions of the source, and a regime may be chosen in which the bulk of the beam ions will be protons. In the present case, we did not seek such a regime for the following considerations. As has been established in (Ref. 1), the fraction of atoms undergoing ionization in a powerful electrical or magnetic field is very appreciably dependent on the conditions under which they are formed. This fraction is greater in the case where H^0 atoms form during the dissociation of /429
H_2^+ or H_3^+ ions, than in the case of simple proton overcharge. If, in addition, we take the fact into account that the field of H^0 atoms per recharging H_2^+ or H_3^+ ions is greater than unity, it thence follows that under the given conditions -- notwithstanding the lesser value of effective electric field $\mathbf{E}^* = |\mathbf{v} \times \mathbf{B}|$ for H^0 atoms with energies of 15 and 10 keV -- we can count on

considerably greater ion capture efficiency in the trap than when a purely proton beam is separated and recharged. We realize, however, that interpretation of the results obtained under such conditions may be extremely difficult. Therefore, in the main version of the apparatus, provision is made for the possibility of passing only one sort of particle through the trap.

Overcharge Chamber. The accelerated beam of hydrogen ions is recharged in a supersonic jet of carbin dioxide. A number of our papers (Ref. 18 - 20) have studied supersonic gas jets discharging into a vacuum and condensing on surfaces cooled to low-temperatures. They demonstrate that such target-jets possess a number of advantages. The chief advantage is the low pressure near the target of optimum thickness (to $1 \cdot 10^{-4}$ N/m^2) and the convenience of working with such gases as CO_2, Ar, and N_2.

Structurally, the recharge chamber was built just as in (Ref. 18), with the one difference being that shape and position of the condenser in relation to the Laval nozzle was changed. Here, the jet is directed from the top downwards, while in previous experiments it was directed from the bottom upwards. This was done in order to prevent the following phenomenon from affecting the vacuum in the recharge chamber: The layer of solid condensate is not always tightly held on the condenser surface; at times it cracks and partially dusts off. Falling onto hot surfaces, the condensate crystals are quickly vaporized and deteriorate the recharge chamber vacuum. As for the shape of the condenser, it, as has been found, does not essentially affect the vacuum in the recharge chamber. (Ref. 20) clarifies this matter in more detail.

Beam Reception Chamber. Its design in the present version of the apparatus is extremely simple, and is clear from Figure 1. It was also made with allowance for new data on the coefficient of injection (Ref. 15), and consists of a heated target of stainless steel and a small condensation pump. It is assumed that a large part of the beam of neutral hydrogen atoms hitting the target will penetrate into it and will no longer influence the process. The same part of the hydrogen which leaves the target must be evacuated by the condensation pump whose evacuation rate is somewhat more than 10 m^3/sec. If, for example, the equivalent current of neutral particles to the target is 10 ma and the coefficient of ion injection is 90%, then at the indicated evacuation rate the reception chamber equilibrium pressure will be about $2 \cdot 10^{-6}$ N/m^2 (under the condition, of course, that hydrogen vapor pressure at the condensation temperature is lower than this value). It may be readily shown, however, that we need not strive for such a low pressure in a reception chamber having the given geometry (diameter of refrigerated channel -- 5 cm, length of this channel -- 20 cm, distance to center of trap -- 80 cm), since even at a pressure of $6 \cdot 10^{-5}$ N/m^2 the equivalent pressure in the trap center, corresponding to the forward stream of hydrogen molecules from the reception chamber, is lower than $1 \cdot 10^{-7}$ N/m^2. /430

In conclusion, we would like to note that final tests of all units of the trap have not yet been finished, but preliminary experiments have yielded quite encouraging results. Thus, without prolonged preliminary processing and without turning on the helium condensation pump, a vacuum of under 10^{-6} N/m^2 has been achieved in the vacuum chamber. The chief difficulty encountered in the first stage of these operations has been in eliminating the so-called "cold" leakages -- leakages appearing when liquid nitrogen, hydrogen, or helium are let into coils or other vessels which have been vacuumized.

Experiments to check the operation of the trap magnetic system have so far been conducted only with the capacitor battery whose parameters were indicated in the introduction. In the first experiments the coils were refrigerated to the nitrogen temperature, and in the subsequent ones -- to the hydrogen temperature. The maximum field in the trap mirrors, obtained at a temperature of 20.4°K and capacitor battery voltage of 5 kV, is around 10.5 ml -- i.e., very close to the computed value. Current rise time from zero to I_{max} was about 0.28 sec. In further experiments, the coils will be powered in accordance with the circuit described in (Ref. 9).

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